LABORATORY EVALUATIONS OF COMPETING UNCOOLED FPA TECHNOLOGIES

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ABSTRACT

Comparison of performance measurements are presented for a Raytheon (Amber) Sentinal Uncooled Micro-Bolometer Focal Plane Array (UMFPA) camera and a Raytheon (formerly Texas Instruments Defense Systems and Electronics Group) Technology Reinvestment Project (TRP) Ferroelectric Uncooled Focal Plane Array (UFFPA) camera. The two cameras were tested for numerous performance-related issues involving time, temperature, FPA region and image translation related dependencies. The performance parameters of interest were 1) nonuniformity versus environmental temperature 2) Changes in non-uniformity with time since power up and as a function of time since non-uniformity correction update, 3) Noise Equivalent Temperature Difference (NETD), 4) V-curves, 5) Minimum Resolvable Temperature Difference (MRTD), 6) response linearity, 7) power consumption and readiness time as a function of system soak temperature, and 8) image smear distortion characteristics.

1.0 INTRODUCTION

1.1 RAYTHEON SENTINEL CAMERA DESCRIPTION

The Sentinel camera tested is a DC coupled system employing a shutter for nonuniformity correction. The temperature of the shutter is neither controlled nor monitored. The Sentinel cameras can be operated off a battery pack or AC power through a converter. This camera comes equipped with a small viewer and the necessary controls required for optimizing the camera parameters. External RS170 and digital image data ports are provided, as is an RS232

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communication port. Information provided for the Raytheon Sentinel UMFPA camera (S/N 161) is as follows: 100 mm, F# 1.0 lens, in band LWIR optical transmission 90%, 320 by 240 pixels (320 by 236 imaging pixels), pixel pitch approximately 48.5 by 48.5 microns, approximately 50% fill factor. This camera has a 30 Hz frame rate and a total field of view (TFOV) 9.108 by 6.717 degrees resulting in a IFOV of 496.76 micro-radians square at the digital port. The system time constant for this camera was measured to be approximately 10.1 msec (NAWC measured value). A second Sentinal camera (S/N 176) with 50 mm F# 0.7 was used to measure noise non-uniformity at hot and cold soak temperatures. These cameras were provided with a single ended digital data port. This output was converted to RS422 using a Raytheon (Amber) Digital Interface Unit (S/N 011). The output digital image data is 12 bit wide with no correction or substitution of bad pixels. A total of 99 bad pixels were observed for camera S/N 0161 and a total of 1089 for camera S/N 0176 (two dead columns and one dead row) resulting is operability of 99.87% and 98.56% respectively. These cameras do not apply any AGC or ALC adjustment to the digital data. The resulting dynamic range of the digital data is approximately –50 to 80 degrees C at 23 degrees C ambient environmental temperature. Camera S/N 0161 was manufactured in March of 1998, and the loaned camera S/N 0176 was of the same vintage.

1.2 RAYTHEON TRP CAMERA DESCRIPTION

The TRP camera tested is an AC system utilizing diffusing micro-lens Silicon chopper for non-uniformity correction. The micro-lens chopper effectively blurs each point in the image scene to an approximate 16-pixel diameter, creating a real time scene based nonuniformity correction. The TRP camera was a prototype using the standard Barium Strontium Titanate (BST) FPA on a prototype electronics package. An AC power converter provided the camera DC power. External RS170 and digital image data ports are provided, as is an RS232 communication port for camera control. A manual camera control box is also available with the essential controls. Information provided by Raytheon for the TRP UFFPA camera is as follows: serial number 004 with 100mm, F# 1.0 lens, in band LWIR optical transmission >90%, 320 by 240 pixels, pixel pitch approximately 48.5 by 48.5 microns, 100% optical fill factor with a reticulated 68% fill factor. The frame rate of this camera is 60 Hz with odd and even frames being composed of different in focus and diffuse images. The camera TFOV is 8.90 by 6.68 degrees resulting in an IFOV 485.45 micro-radians square at the digital port. The time constant of this sensor is approximately 15 msec (Manufacturers stated value). Date of manufacture of this camera is unknown.

The digital data format produced by this camera is a single ended 14 bit wide raw data. Dead/deviant pixels are substituted in the camera electronics prior to digital data output. The camera uses AGC and ALC to provide extended dynamic range of operation and to allow maximization of sensitivity for low contrast scenes. Digital data output by the camera is a combination of two sub-frames of data, where each sub-frame is a difference between a focused image and blurred image; (F1-D1), (D1-F2), and (F2-D2), for example. Two consecutive sub-frames are then differenced in order to form an output frame. The sign (polarity) of every output frame is then changed. Thus the digital data coming out of the camera takes on the form of F1+F2-2D1 or 2F2-D1-D2. The two forms differ in that one uses the same focused image and two different defocused images to form a frame of digital image data, while the other uses two different focused images and the same defocused image in order to form the image data. These two combinations of sub-frame manipulation produce different blurring effects when viewing moving objects.

The test data for both cameras was gathered using consistent measurement techniques, the same personnel, identical test equipment and setups, and the same environmental conditions. This test data is to be used for direct comparisons of these two different uncooled technologies and not as absolute measurement values. The data presented in some cases does not match either the manufacturers specified or previously reported data available. This type of discrepancy is partly due to the differences in blackbody calibration, collimator thruput, and optical losses encountered in the equipment used, etc. This can also be partly due to the differences in data format used for these tests. All image data reported is through the use of full width digital data port, and not the RS170 camera output.

2.0 TEST RESULTS

The cameras were housed in a temperature controlled environmental chamber for approximately 1 hour prior to conducting all the temperature dependence test cycles. This soak duration permitted the cameras and optical lens assemblies to equilibrate in order to simulate operational conditions. All the image data was captured via an open port in the chamber, eliminating any possibility of additional noise and distortion produced by a window. Unless otherwise noted, all data on the Sentinel was taken with S/N 0161.

2.1 POWER COMSUMPTION

Table 1 details the approximate power consumption of the two different camera head assemblies at three soak temperatures. The power converters and digital data RS422 conversion are omitted for both cameras. The Sentinel camera power consumption measurement includes a liquid crystal display (LCD) that could not be removed for this measurement. Both peak powers required to start the cameras and steady state power required to operate the cameras is reported.

Table 1. Camera Power Consumption.

Camera	Cold soak power (≈4C)	Ambient power (≈23 degrees C)	Hot soak power (≈40 degrees C)
Sentinel	20.5W peak, 14.7W ss*	22.7W peak, 15.2W ss	20.7W peak, 17.5W ss
TRP	10.3W peak, 7.2W ss	9.6W peak, 5.8W ss	10.8W peak, 7.0W ss

* ss = steady state

The TRP camera showed a substantially lower power consumption and peak power required to start the camera even though it uses a rotating chopper in its design. Both cameras responded differently to the temperature environment. The Sentinel steady state rose with increasing temperature indicating that the thermo-electric (TE) cooler may be set for low temperature operation. The TRP camera had a minimum power consumption at room temperature indicating a TE setting at an elevated temperature as was confirmed from the manufacturer, TE operation of the BST FPA is at a 22 degree C set-point.

2.2 OPERATIONAL READINESS TIME

The operational readiness time is defined as the time that it takes for a camera to output the first image frame after application of power. The operational readiness time of the Sentinel was measured at approximately 45 seconds, while the TRP was measured at approximately 35 seconds. The operational readiness time was determined to be independent of soak temperature for both cameras. This result is somewhat surprising since a TE cooler requires a longer period of time to change the FPA temperature and stabilize at its set point. It appears that greater temperature delta will be required to see this effect in an operational system.

2.3 PIXEL OPERABILITY

The 12 bit digital image data produced by the Sentinel camera is not corrected or substituted for bad pixels. A total of 99 bad pixels were observed for camera S/N 0161 and a total of 1089 for camera S/N 0176 (two dead columns and one dead row) resulting in an operability of 99.87 and 98.56% respectively. The camera with dead rows and columns shows visible effects when viewing an image of a object was both translated and stationary in that area of the FPA. This can be very detrimental depending on the application.

Due to our limited understanding of the TRP camera software and circuitry we were unable to extract the dead/deviant pixel maps. This information is not available at the digital data port due to prior substitution and processing necessitated by the frame processing used to form an image. The TRP camera showed no visible effects of dead or deviant pixels in any imagery collected at either the digital or RS170 ports.

2.4 SYSTEM BLUR SPOT SIZE

The system blur spot was estimated by projecting a 4-bar pattern through a collimator and examining the spatial spreading of the bar edges. The bar pattern was aligned parallel to rows and columns of the FPA under test. Multiple data files were collected their individual estimates are averaged and a standard deviation is calculated to determine the system blur spot and a repeatability error of the estimate.

The Sentinel S/N 0161 camera system blur spot was estimated to be 1.92 pixels in diameter with a standard deviation of 0.12 pixels, at the digital port output. The blur value is the same in both directions on the FPA leading to the conclusion that the blur spot is circular in shape.

The TRP camera measured system blur spots are 3.34 pixels with a standard deviation of 0.37 across the columns and 2.78 pixels with a standard deviation of 0.16 across the rows, at the digital port output. This non-symmetrical shape can be accounted for by two facts. First, the detector Read Out Integrated Circuit has a small amount of electrical cross talk in the horizontal direction. This causes a slight degradation in the quality of focus. Second, the camera as tested has a slight amount of geometric distortion in the image caused by system timing differences from the RS-170 video format standards. In other words, the camera aspect ratio is not exactly 4 by 3. These two details combine to cause the non-symmetrical blur spot.

2.5 MINIMUM RESOLVABLE TEMPERATURE DIFFERENCE

The Minimum Resolvable Temperature Difference comparison of the Sentinel and TRP cameras is shown in Figure 1. The MRTD of both cameras were evaluated with the same equipment, setup and personnel in order to produce a meaningful comparison.

It is unclear why the MRTD of the TRP camera is consistently lower than that of the Sentinel camera given that the Sentinel’s blur spot estimation and noise characteristics are lower than the TRP’s and while both cameras possess roughly identical resolution (IFOV). The use of automatic gain and level controls by the TRP camera may account for the difference. Also use of different collimator substantially improved the MRTD values for the TRP camera, reducing the MRTD value by 3X. Comparison of the two cameras using this collimator is not available and thus the only data available for comparison between these two cameras is shown in figure 1.

2.6 SPATIAL NOISE (FIXED PATTERN NOISE)

Spatial noise is the component of noise from multiple sources that does not change with time or changes in a extremely slow manner relative to the frame rate. It is typically due to pixel to pixel variations in gain, responsivity, and electronic noise. Here spatial noise is defined as the standard deviation of the camera's response to a scene that was generated by taking an average of a large number of frames of an ideal uniform scene.

Due to significant differences in the design of the two cameras, it is not reasonable to look at the spatial noise numbers as a comparison between the two cameras. It is necessary to scale the differences in some manner in order to make these comparisons. For our comparisons of spatial noise we determined the signal to noise ratio (SNR) of the two cameras assuming that the full A/D range is available while only using spatial noise as the limiting factor in our calculations. In these comparisons the camera with the highest SNR has a better performance characteristic for the given conditions that the data was measured under. The measurement parameters, camera soak temperature, blackbody scene temperature, region of UFPA measured were identical for this data set. Tables 2 and 3 detail some of the spatial noise limited SNR calculations for both cameras, from data measured under similar environmental conditions with the same measurement equipment, personnel, and techniques. Please note several of the full array tables show the TRP cameras results for the 23-degree C soak as “No data.” This fact is easily explained by the scene-based non-uniformity correction of the diffusing chopper. When looking as a full-field constant temperature scene, the AC-coupled nature of the camera effectively subtracts out all the signal. The result of this is that only temporal noise is present. At the extreme temperatures there is a small amount of energy offset due to the imperfect diffusion of light by the chopper. This offset appears to be signal to the detector, and allows the non-uniformities to be present. It is often difficult and meaningless to attempt these types of full-field measurements without inserting a large temperature pedestal with the blackbody source. In the case where smaller target sizes are used, this effect is dramatically reduced and measurement data is more meaningful.

Table 2. Center 80X60 Pixel Camera Spatial Noise Limited SNR Calculations.

BB Scene Temp ©	≈3 degree C soak T		≈23 degree C soak T		≈40 degree C soak T	
	Sentinel	TRP	Sentinel	TRP**	Sentinel	TRP
2	1446	759	1165	145	118*	450
10	3087	910	1513	238	571	495
20	762	1080	2109	793	834	618
30	471	881	2941	784	1026	787
40	371	702	3046	445	2002	1016
50	326	537	2221	280	1223	754
60	302	406	1396	200	820	919
70	280	300	1037	151	211	639
80	265	236	94*	122	56*	507

**Indicates potential saturation or starvation of the data (dynamic range limitations).*
***Indicates region examined is center 20x20 or 80x80 pixels due to TRP data set employed.*

Table 3. Full Frame Camera Spatial Noise Limited SNR Calculations.

BB Scene Temp (C)	≈3 degree C soak T		≈23 degree C soak T		≈40 degree C soak T	
	Sentinel	TRP	Sentinel	TRP	Sentinel	TRP
2	1061	304	391	No data	124*	116
10	1468	405	450	No data	455	131
20	584	491	553	No data	677	161
30	348	311	636	No data	845	212
40	259	188	621	No data	1315	316
50	218	135	538	No data	808	266
69	195	102	363	No data	421	261
70	176	77	319	No data	128	168
80	162	63	85*	No data	46*	128

**Indicates potential saturation or starvation of the data (dynamic range limitations).*

Significant changes in the spatial noise limited SNR is observed for both cameras as the black body temperature changes and as the cameras environmental soak temperature is varied. These differences are significant and the performance characteristics of these cameras will vary greatly under different environmental conditions. Note that this comparison is for the specific camera, camera mode of operation, and environmental conditions the data was collected under. Changes in any of these parameters may result in different values of camera performance. Also note that the Sentinel camera shows limitations in its dynamic range at the hot and cold temperature extremes, which limit camera performance at those points.

2.7 TEMPORAL NOISE

Temporal noise is a measure of the time varying noise across the focal plane array. This is the component of noise that changes in an extremely fast manner, frame to frame while imaging an ideal uniform scene. This noise is typically due to variations in scene energy emission, UFPA noise, and electronic noise. Here temporal noise is defined as the measure of the standard deviation of each pixel’s response resulting from a pixel by pixel examination of a large number of frames taken while looking at an ideal uniform scene.

Due to significant differences in the design of the two cameras, it is not reasonable to look at the temporal noise numbers as a comparison between the two cameras. It is necessary to scale the differences in some manner in order to make these comparisons. For our comparisons of temporal noise we determined the SNR of the two cameras assuming that the full A/D range is available while only using spatial noise as the limiting factor in our calculations. In these comparisons the camera with the highest SNR has a better performance characteristic for the given conditions that the data was measured under. The measurement parameters, camera soak temperature, blackbody scene temperature, region of UFPA measured were identical for this data set. Tables 4 and 5 detail some of the temporal noise limited SNR calculations for both cameras, from data measured under similar environmental conditions with the same measurement equipment, personnel, and techniques.

Table 4. Center 80X60 Pixel Camera Temporal Noise Limited SNR Calculations.

BB Scene Temp (C)	≈3 degree C soak T		≈23 degree C soak T		≈40 degree C soak T	
	Sentinel	TRP	Sentinel	TRP**	Sentinel	TRP
2	3303	2550	1664	554	3274	2939
10	3552	2601	1994	553	3094	2965
20	3516	2686	2781	549	3220	2939
30	2592	2632	2504	567	2656	2837
40	3101	2697	2384	548	3269	2742
50	2901	2621	2909	552	3233	2719
60	3259	2621	2646	558	3203	2926
70	2013	2675	2111	552	2627	2979
80	775*	2697	2286	556	2114	2939

**Indicates potential saturation or starvation of the data (dynamic range limitations).*
***Indicates region examined is center 20x20 or 80x80 pixels due to TRP data set employed.*

Table 5. Full Frame Camera Temporal Noise Limited SNR Calculations.

BB Scene Temp (C)	≈3 degree C soak T		≈23 degree C soak T		≈40 degree C soak T	
	Sentinel	TRP	Sentinel	TRP	Sentinel	TRP
2	3259	2590	1469	No data	3103	2913
10	3471	2560	1918	No data	3043	2926
20	3468	2632	2591	No data	3173	2900
30	2532	2632	2397	No data	2606	2979
40	3059	2653	2291	No data	3173	2874
50	2852	2653	2734	No data	3043	2675
69	3210	2697	2517	No data	3153	2939
70	1980	2719	1978	No data	2578	2926
80	716*	2731	2212	No data	2077	2926

**Indicates potential saturation or starvation of the data (dynamic range limitations).*

Examination of the data indicates that the two cameras perform similarly in terms of temporal noise for virtually all the data presented. The exception is the 23 degree C data set which indicates a reduced SNR for the TRP camera and at extreme scene temperatures indicating the Sentinel cameras dynamic range limits. The TRP exhibits better consistency at the scene temperature extremes, which may be an indication of a greater dynamic range of this camera. Both cameras show a variation in the temporal noise limited SNR although significantly less then the spatial component counterpart. Note that this comparison is for the specific camera, camera mode of operation, and environmental conditions the data was collected under. Changes in any of these parameters may result in different values of camera performance.

2.8 TOTAL NOISE

Total noise is the Root-Sum-Square (RSS) of the temporal, spatial, and any other separately definable noise sources. Total noise is given by the following equation:

$$\text{TotalNoise} = \left\{ (N_t)^2 + (N_s)^2 + (N_?)^2 + \cdots \right\}^{1/2}$$

Because the noise was measured for the particular camera as a system, this total noise contains the spatial and temporal noise components listed above.

Following the same protocol as above, the SNR is used as the parameter for comparing the total noise of the system. The tables below detail some sample total noise limited SNR calculations for both cameras, from data measured under similar environmental conditions using similar measurement equipment, personnel, and techniques.

Table 6. Center 80x60 Pixel Camera Total Noise Limited SNR Calculations.

BB Scene Temp (C)	≈3 degree C soak T		≈23 degree C soak T		≈40 degree C soak T	
	Sentinel	TRP	Sentinel	TRP**	Sentinel	TRP
2	1326	728	954	141	118*	445
10	2330	859	1205	219	561	489
20	745	1002	1681	451	807	604
30	464	835	1907	459	957	758
40	368	680	1878	345	1707	953
50	324	526	1765	249	1144	727
60	300	401	1234	188	794	877
70	277	298	931	145	211	625
80	250	235	94*	119	56*	499

**Indicates potential saturation or starvation of the data (dynamic range limitations).*
***Indicates region examined is center 20x20 or 80x80 pixels due to TRP data set employed.*

Table 7. Full Frame Camera Total Noise Limited SNR Calculations.

BB Scene Temp (C)	≈3 degree C soak T		≈23 degree C soak T		≈40 degree C soak T	
	Sentinel	TRP	Sentinel	TRP	Sentinel	TRP
2	1009	302	378	No data	124*	116
10	1352	400	438	No data	450	131
20	576	483	540	No data	662	160
30	345	309	615	No data	804	212
40	258	188	599	No data	1214	314
50	218	135	528	No data	781	265
69	195	102	359	No data	417	260
70	175	77	315	No data	128	168
80	158	63	85*	No data	46*	127

**Indicates potential saturation or starvation of the data (dynamic range limitations).*

Examination of the data in Tables 6 and 7 indicates that the Sentinel camera has higher S/N values then the TRP in terms of total noise for virtually all of the full frame data and for the 23 and 40 degrees C soak temperatures, center 80x60 pixel region data (except extreme scene temperatures). The TRP performs better for most of the 3 degrees C soak temperature, center 80x60 pixel region data, and at the scene temperature extremes. Note that this comparison is for the specific camera, camera mode, and environment the test data was collected under. Changes in any of these parameters may result in different conclusions of camera performance.

2.9 SINGLE FRAME NOISE

Single frame noise is the standard deviation of the response from a single frame of data taken when viewing an ideal uniform source. It includes effects of both spatial and temporal noise components, but is not the same as the RSS of the spatial and temporal noise components (total noise) since the temporal noise varies randomly from frame to frame.

Following the same protocol as above, the SNR is used as the parameter for comparing the single frame noise of the system. The tables below detail some sample single frame noise limited SNR calculations for both cameras, from data measured under similar environmental conditions using similar measurement equipment, personnel, and techniques.

Table 8. Center 80x60 Pixel Single Frame Noise Limited SNR Calculations.

BB Scene Temp (C)	≈3 degree C soak T		≈23 degree C soak T		≈40 degree C soak T	
	Sentinel	TRP	Sentinel	TRP**	Sentinel	TRP

2	1349	372	1080	140	118*	327
10	2326	389	1354	217	564	338
20	741	404	1751	448	804	378
30	469	382	2103	462	984	401
40	368	377	2088	348	1699	437
50	325	338	1781	246	1147	403
60	300	303	1273	189	794	433
70	280	249	965	145	211	376
80	264	207	95*	119	56*	348

**Indicates potential saturation or starvation of the data (dynamic range limitations).*
***Indicates region examined is center 20x20 or 80x80 pixels due to TRP data set employed.*

Table 9. Full Frame Camera Single Frame Noise Limited SNR Calculations.

BB Scene Temp (C)	≈3 degree C soak T		≈23 degree C soak T		≈40 degree C soak T	
	Sentinel	TRP	Sentinel	TRP	Sentinel	TRP
2	1012	251	387	No data	123*	112
10	1361	298	444	No data	450	127
20	576	331	541	No data	665	154
30	347	258	622	No data	819	193
40	258	173	608	No data	1210	266
50	218	128	523	No data	786	232
69	195	100	363	No data	418	230
70	176	76	317	No data	128	158
80	162	63	86*	No data	46*	124

**Indicates potential saturation or starvation of the data (dynamic range limitations).*

Examination of the data in Tables 8 and 9 indicates that the Sentinel camera has a higher SNR values than the TRP in terms of single frame noise for all of the full frame and all of the center 80x60 data (except at extreme scene temperatures). Note that this comparison is for the specific camera, camera mode, and environment the test data was collected under. Changes in any of these parameters may result in different conclusions of camera performance.

2.10 NON-UNIFORMITY

Non-uniformity is defined as the spatial noise divided by the mean response of the averaged frame. Data for environmental soak temperatures of 3(+/-1), 23(+/-1) and 40(+/-1) degrees C at varying scene temperatures have been reduced to determine how the temperature of the environment affects camera non-uniformity characteristics. The tables below detail some sample non-uniformity calculations for both cameras, from data measured under similar environmental conditions using similar measurement equipment, personnel, and techniques.

Table 10. Center 80x60 Pixel Non-uniformity Calculations.

BB Scene Temp (C)	≈3 degree C soak T		≈23 degree C soak T		≈40 degree C soak T	
	Sentinel	TRP	Sentinel	TRP**	Sentinel	TRP
2	0.230%	0.263%	0.308%	2.496%	11.701%*	0.446%
10	0.095%	0.220%	0.207%	1.384%	1.579%	0.405%
20	0.329%	0.185%	0.127%	0.372%	0.729%	0.325%
30	0.464%	0.227%	0.078%	0.365%	0.423%	0.255%
40	0.509%	0.285%	0.066%	0.606%	0.168%	0.198%
50	0.502%	0.372%	0.080%	0.927%	0.217%	0.314%
60	0.474%	0.492%	0.113%	1.239%	0.265%	0.219%
70	0.450%	0.667%	0.135%	1.570%	0.861%	0.314%
80	0.423%	0.847%	1.338%*	1.858%	2.847%*	0.396%

**Indicates potential saturation or starvation of the data (dynamic range limitations).*
***Indicates region examined is center 20x20 or 80x80 pixels due to TRP data set employed.*

Table 11. Full Frame Camera Non-uniformity Calculations.

BB Scene Temp (C)	≈3 degree C soak T		≈23 degree C soak T		≈40 degree C soak T	
	Sentinel	TRP	Sentinel	TRP	Sentinel	TRP
2	0.313%	0.658%	0.923%	No data	10.828%*	1.721%
10	0.200%	0.494%	0.696%	No data	1.938%	1.522%
20	0.431%	0.407%	0.486%	No data	0.888%	1.244%
30	0..632%	0.642%	0.363%	No data	0.512%	0.942%
40	0.734%	1.059%	0.325%	No data	0.256%	0.632%
50	0.757%	1.481%	0.330%	No data	0.330%	0.883%
69	0.740%	1.960%	0.435%	No data	0.519%	0.764%
70	0.724%	2.574%	0.441%	No data	1.435%	1.189%
80	0.699%	3.172%	1.478%*	No data	3.504%*	1.564%

**Indicates potential saturation or starvation of the data (dynamic range limitations).*

Examination of the data would indicate that the Sentinel camera has a lower non-uniformity than the TRP camera for all full frame data and nearly all of the center 80x60 data (except at extreme scene temperatures and a portion of the cold soak data). Note that this comparison is for the specific camera, camera mode, and environment the test data was collected under. Changes in any of these parameters may result in different conclusions of camera performance.

2.11 NON-UNIFORMITY VS. TIME

The variation of non-uniformity with time was found to be very stable if the non-uniformity correction of the Sentinel is applied prior to the collection of each timed data point. Note that the TRP uses a real time scene based non-uniformity correction, which is applied on a frame to frame basis in real time. Note that this comparison is for the specific camera, camera mode, and environment the test data was collected under. Changes in any of these parameters may result in different conclusions of camera performance.

2.12 NON-UNIFORMITY VS. OFFSET CORRECTION

This test does not apply to the TRP camera since it uses a real time defocus chopper in order to provide a scene based offset non-uniformity correction to all camera data. The Sentinel camera's non-uniformity was found to degrade slightly over time. Table 12 below shows how the non-uniformity of the Sentinel camera degrades with time since the last non-uniformity update. Note that the Sentinel camera was operating for approximately 1 hour prior to beginning this test. Also, note that this data is for the specific camera, camera mode, and environment the test data was collected under. Changes in any of these parameters may result in different conclusions of camera performance.

Table 12. Sentinel Non-uniformity vs. Time
Since Last NUC Update at 26C Soak Temperature.

Time Since NUC Update (minutes)	Region of UFPA Used In Non-uniformity evaluation				
	Center 40x30	Center 80x60	Center 160x120	Center 240x180	Center 320x236
0.1	0.00067	0.00087	0.001512	0.002784	0.00443
1	0.0007	0.00089	0.001546	0.002812	0.00454
5	0.00073	0.0009	0.001536	0.003158	0.00544
11	0.00077	0.00094	0.001629	0.003454	0.00625
20	0.0009	0.00103	0.001771	0.003931	0.00744
30	0.00091	0.00107	0.001901	0.004308	0.00837
60	0.00095	0.00113	0.002026	0.004586	0.00922

**Non-uniformity is defined as the spatial noise divided by the mean response for the given region.*

***Camera in operation approximately one hour before beginning to take data.*

2.13 SINGLE FRAME NON-UNIFORMITY

For single frame non-uniformity, the spatial noise is replaced with single frame noise to create single frame non-uniformity. This measurement of single frame non-uniformity is typically what a system must deal with in an operational sense, since most systems do not employ frame averaging or running averages. The tables below detail some sample single frame non-uniformity calculations for both cameras, from data measured under similar environmental conditions using similar measurement equipment, personnel, and techniques.

Table 13. Center 80x60 Pixel Single Frame Non-uniformity Calculations.

BB Scene Temp (C)	≈3 degree C soak T		≈23 degree C soak T		≈40 degree C soak T	
	Sentinel	TRP	Sentinel	TRP**	Sentinel	TRP
2	0.247%	0.528%	0.333%	2.585%	11.750%*	0.614%
10	0.126%	0.504%	0.231%	1.526%	1.598%	0.594%
20	0.338%	0.470%	0.153%	0.659%	0.756%	0.532%
30	0.467%	0.519%	0.109%	0.619%	0.441%	0.501%
40	0.512%	0.513%	0.096%	0.775%	0.198%	0.460%
50	0.504%	0.555%	0.100%	1.054%	0.232%	0.585%
60	0.477%	0.588%	0.124%	1.312%	0.273%	0.464%
70	0.450%	0.676%	0.145%	1.632%	0.862%	0.534%
80	0.425%	0.795%	1.330%*	1.902%	2.856%*	0.576%

**Indicates potential saturation or starvation of the data (dynamic range limitations).*
***Indicates region examined is center 20x20 or 80x80 pixels due to TRP data set employed.*

Table 14. Full Frame Camera Single Frame Non-uniformity Calculations.

BB Scene Temp (C)	≈3 degree C soak T		≈23 degree C soak T		≈40 degree C soak T	
	Sentinel	TRP	Sentinel	TRP	Sentinel	TRP
2	0.328%	0.796%	0.933%	No data	10.866%*	1.779%
10	0.216%	0.672%	0.706%	No data	1.959%	1.578%
20	0.437%	0.604%	0.496%	No data	0.905%	1.298%
30	0.635%	0.775%	0.371%	No data	0.528%	1.035%
40	0.737%	1.156%	0.332%	No data	0.278%	0.752%
50	0.759%	1.554%	0.339%	No data	0.339%	1.006%
69	0.742%	2.004%	0.435%	No data	0.523%	0.893%
70	0.724%	2.632%	0.444%	No data	1.436%	1.262%
80	0.699%	3.171%	1.471%*	No data	3.512%*	1.610%

**Indicates potential saturation or starvation of the data (dynamic range limitations).*

Examination of the data would indicate that the Sentinel camera has a lower non-uniformity than the TRP for all full frame data and all of the center 80x60 data (except at extreme scene temperatures). Note that this comparison is for the specific camera, camera mode, and environment the test data was collected under. Changes in any of these parameters may result in different conclusions of camera performance. Also, note that the Sentinel camera shows limitations in its dynamic range at the hot and cold temperature extremes, which limit camera performance.

2.14 NON-UNIFORMITY VS. BACKGROUND TEMPERATURE (V-CURVE)

For a given set of camera and environmental parameters, relative non-uniformity can be plotted as a function of the blackbody image scene temperature. These types of plots show visually how the non-uniformity varies with the scene temperature at the given environmental soak temperature. What is desired is that the response of the camera be relatively flat across all scene temperatures (a very shallow or flat V shape).

For a camera employing a fixed temperature shutter to perform single point offset non-uniformity corrections (Sentinel), one would expect the best non-uniformity to occur when the scene temperature and the shutter temperature are identical. Then as the scene to shutter temperature delta grows larger, non-uniformity will degrade (increase). Figure 2 shows that this is approximately what happens for the Sentinel camera V-curves at 3 degrees C soak temperature. Figures 3 and 4 show that at 26 and 40 degrees C soak temperatures respectively, the data is relatively flat over a large portion of the range of scene temperatures. At the extreme scene temperature to shutter temperature deltas, the camera begins to reach dynamic range limits and the non-uniformity increases drastically beyond these points.

For a system that employs a real time defocusing chopper for non-uniformity correction (TRP), one would expect the best non-uniformity values to be at the FPA set point temperature and to be similar in value across all other hotter and colder scene temperatures. However, this is not always the case for the TRP system. Figures 5, 6, and 7 show the v-curves for the TRP camera over a wide range of scene temperatures for 3, 26, and 40 degrees C soak temperatures, respectively. For full frame data, the non-uniformity is best when the camera soak temperature and the scene temperature are identical and degrades in a close to linear fashion as the scene temperature changes from the soak temperature. This would imply that the diffusing chopper is affected by emissions from the chopper surface or other internal camera surfaces in addition to the scene. This full frame effect can be reduced by better control of stray light and camera housing emissions. For the central 40x30 pixel region, the diffusing chopper performs as expected, where non-uniformity remains relatively constant (flat) across all presented scene temperatures, regardless of the soak temperature.

2.15 NOISE EQUIVALENT TEMPERATURE DIFFERENCE (NEDT)

NETD is typically measured using full frames of data and calculated by using the following formula:

$$\text{NETD} = \Delta T\,(V_N/\Delta V_S)$$

where:

ΔT = differential temperature in degrees C
V_N = RSS of all noise source
ΔV_S = change in mean signal caused by the differential temperature used

For the Sentinel camera system tested (S/N 0161 at 23 degrees C and S/N 176 at 3 and 40 degrees C), data was collected from two blackbody targets at known temperatures. The average signal and the RSS of all noise components (spatial and temporal noise) was then calculated for various regions in the array for both blackbody scenes at the two blackbody scene temperatures which provided the best noise performance. All dead pixels are removed from the data prior to performing calculations. The results are shown in Table 15 below.

Table 15. Sentinel Camera NETD Calculations.

	Camera S/N 0176 3 degrees C Soak T	Camera S/N 0161 26 degrees C Soak T	Camera S/N 0176 40 degrees C Soak T
NETD (center 40x30)	117 mK	71 mK	63 mK
NETD (full frame 320x236)	177 mK	248 mK	108 mK

The Sentinel camera manufacturers specification of NETD was <70 mK at a background temperature of 25 degrees C (using 50mm, F# 0.7 optics) over an undefined region of the UFPA.

Since the TRP camera system tested is AC coupled and uses a defocusing chopper, the above methodology will not result in valid measurements of NETD. The following methodology was provided by the manufacturer to measure the NETD. For the TRP camera system, an edge target (step function) with a known differential temperature was projected through a 120-inch collimator and presented to the camera. The maximum and minimum response along each side of the edge target (step function) was recorded for a few pixels. The total noise (RSS of temporal and spatial noise components) was then calculated from the same pixel regions of the UFPA as the signal and the above formula was then used to calculate NETD. This result is corrected for atmospheric transmission and collimator transmission losses to obtain a final NETD value. Note the NETD was only calculated for the 23 (+/-1) degree C environmental temperature due to the equipment and methodology required making the measurement. The manufacturers measured value of NETD was approximately 60 mK (fax from Bob Nicklin, RSC, dated 28 July 1998; specific region of UFPA evaluated is block [296,218] to [336,256]). This is approximately 25% better than the NAWC measured value of 76mK (average NETD of 42 pixels).

Using the above methodology it is not possible to obtain TFOV (full frame) NETD values for the TRP camera. It is also unknown how soak temperature would affect measured NETD values for the TRP camera. Finally, the TRP NETD was measured with AGC and ALC on, with maximum gain. It is unclear how the NETD would change if the AGC and ALC are turned off and the camera set to image a wide temperature range, but NETD would likely increase.

2.16 IMAGE SMEAR/DISTORTION DUE TO IMAGE MOTION

Imaging an object with constant rate camera motion (constant linear or angular rate) can be used to characterize the smearing and/or distortion effects in an image caused by the integration time, time constant, and/or readout methodology of the sensor under test. The two cameras were mounted on a rate table capable of accurate, constant rates of angular rotation. An image was projected within the center of the field of view of the sensor, using a collimator and a known target of specified shape, delta temperature, and angular extent. The rate table was rotated at a constant angular rate through the target image while recording digital data. This process was repeated for all constant angular rates (0,1,2,3,4,5,6,7,8,9,10, -1, -2, -3, -4, -5, -6, -7, -8, -9, and -10 degrees per second), all sensor orientations (0, 45, 90, and 135 degrees), camera frame rates, and for target object contrast ratio of interest. This data was post processed in order to determine the image smearing caused by the interaction of the sensor integration time and readout methodology at the constant angular rates.

Figures 8 and 9 show a series of traces of a cross section of a bar target at 0 and 4 degree per second angular rate respectively, for the TRP camera. Figures 10 and 11 show the same motion rate data for a Sentinel camera, respectively. These figures are shown as an example of the distortion and smearing that occurs during the translation of an image across the FPA.

Summary of this measurement series for the Sentinel camera S/N 0161 are listed below.

Measured smear is less than theoretical smear calculations by approximately 30 to 41% for all reduced frames of data. The reason for this is unknown and is still under investigation. The smearing is repeatable. It is possible that noise filters in the UFPA camera electronics are responsible for this large discrepancy, but closure of this item has not been reached to date.

Measured smear in the center of the TFOV is independent of the camera orientation, based on the small set of reduced data. Note the camera orientation determines the direction of the image flow across the pixel grid in the UFPA when imaging a scene under constant angular rate motion.

The measured distortion caused by the ripple mode readout under constant angular rate motion is very similar to that calculated by theoretical means, and thus is predictable and repeatable.

Summary of this measurement series for the TRP camera is listed below.

Due to the AC coupling/diffusing chopper combination tested, the target edges exhibit overshoot/undershoot edge enhancements in the image data. These edge anomalies make it difficult to compare measured smear to theoretical smear values. The cause of these edge anomalies is a set of electrical filters in the ROIC circuitry of the TRP camera.

The most interesting feature of the smear data is that the width of the Full Width Half Maximum (FWHM) response to a single bar of the 4-bar target pattern does not change with angular rate. It remains constant, approximate 15.5-16 pixels wide for 0, 90, 180, and 270-degree camera orientations and approximately 22-23 pixels wide for 45, 135, 225, and 315-degree camera orientations, regardless of the constant angular rate applied. In addition, the slope of the rising and falling edges remains very similar, regardless of the constant angular rate. This means that the edges in the scene will remain more spatially correlated than the DC coupled micro-Bolometer cameras tested. This feature would allow certain template-matching algorithms to work more efficiently and be easier to implement.

The measured distortion (skewed linear features) caused by the ripple mode readout (row by row) under constant angular rate closely matches that calculated by theoretical methods Thus; this distortion is predictable and repeatable.

3.0 SUMMARY

The test results show that the performance characteristics of the two technologies, Ferroelectric FPA (TRP camera) and the micro-Bolometeric FPA (Sentinel camera) are very viable for numerous applications. Each technology has advantages in performance and behavior under different environmental and scene conditions. The TRP camera has a scene based non-uniformity correction, low power consumption, good performance at temperature extremes, and a unique resistance to image smearing due to image motion. The Sentinel camera showed excellent non-uniformity and a low SNR throughout its range of operation. Both cameras under identical test conditions show similar MRTD values indicating comparable performance. It is unfortunate that we were not able to measure the MRTD of the Sentinel camera using the longer focal length collimator in order to make a direct comparison to the TRP, which showed a improvement in its MRTD value by a factor of three over the data reported in Figure 1. The data in this comparison study shows that decisions for applications of these sensors should be based on application dependent criteria.

4.0 ACKNOWLEDGMENTS

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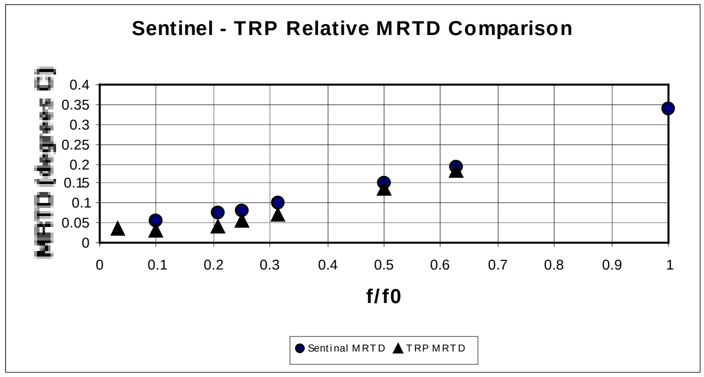

Figure 1. MRTD Comparison of the Raytheon Sentinel and TRP Cameras.

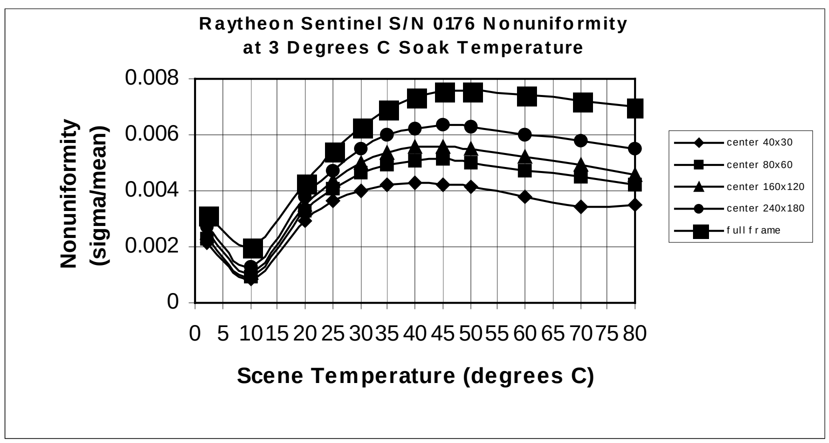

Figure 2. V-Curves for 3 degrees C Environmental Soak of Sentinel Camera (Non-Uniformity of 1 = 100%).

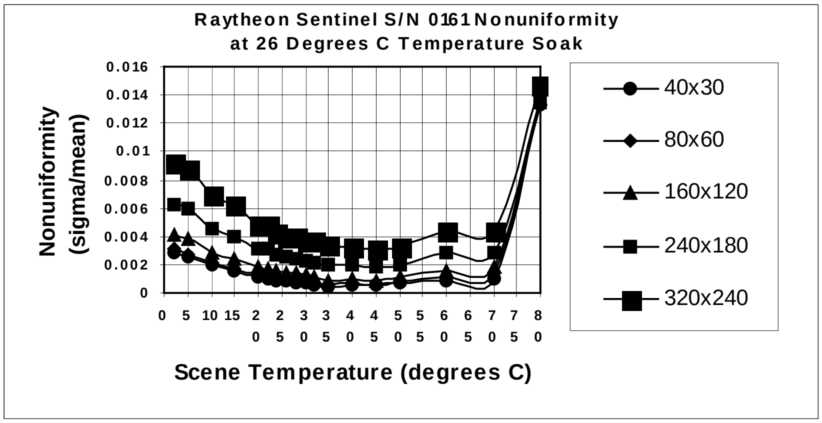

Figure 3. V-Curve 26 Degrees C Environmental Soak of Sentinel Camera (Non-Uniformity of 1 = 100%).

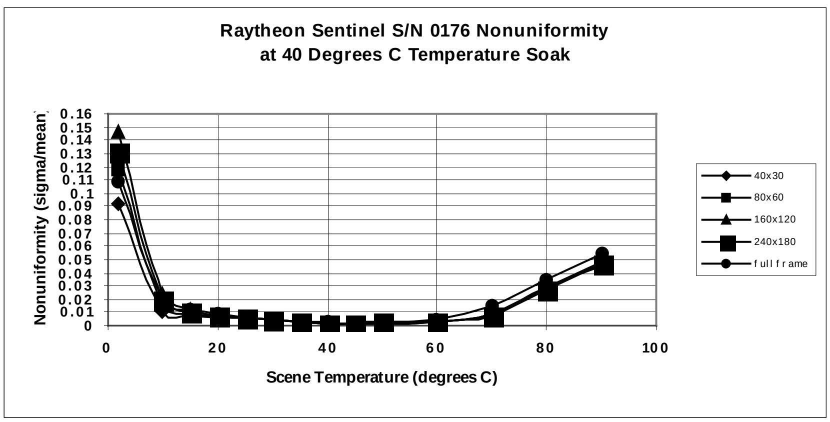

Figure 4. V-Curve for 40 Degrees C Environmental Soak of Sentinel Camera (Non-Uniformity of 1 = 100%).

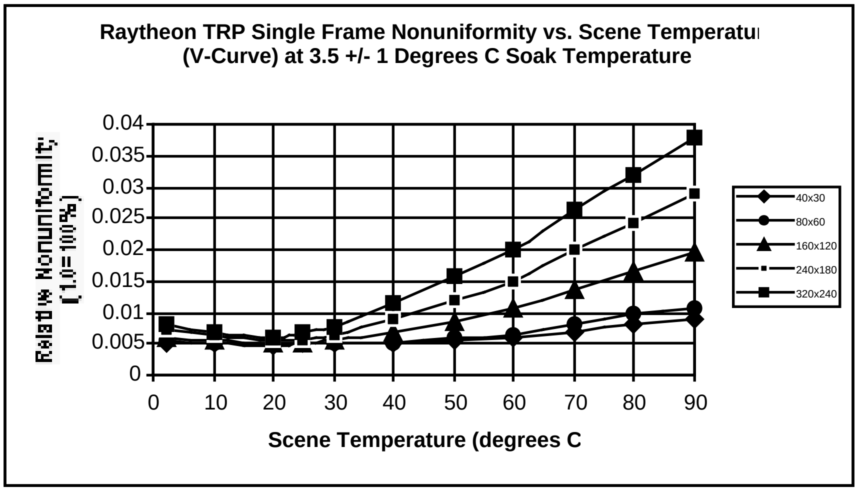

Figure 5. V-Curve for 3 Degrees C Environmental Soak of TRP Camera.

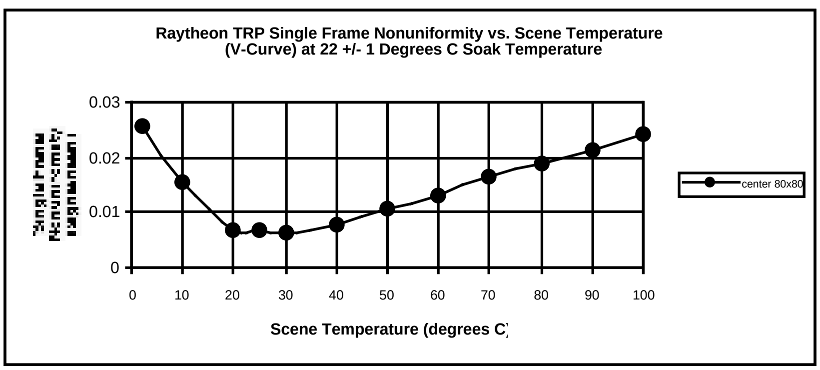

Figure 6. V-Curve for 22 Degrees C Environmental Soak of TRP Camera (Non-Uniformity of 1 = 100%).

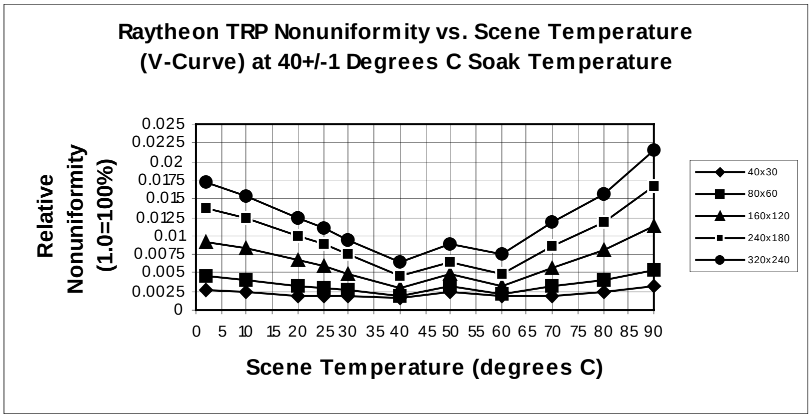

Figure 7. V-Curve for 40 Degrees C Environmental Soak of TRP Camera.

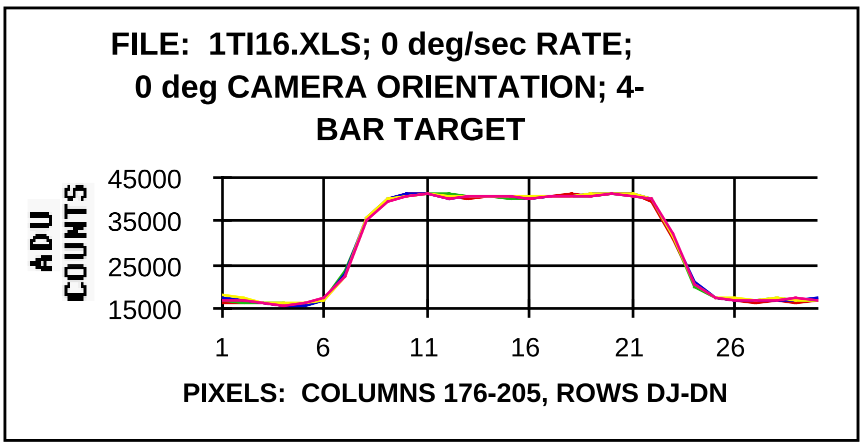

Figure 8. Stationary Bar Target Cross-Section With TRP Camera.

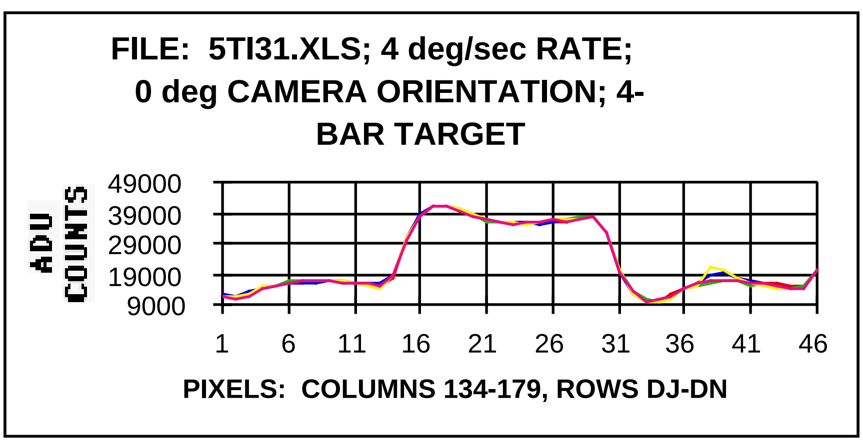

Figure 9. 4 Degrees/Second Rotation Rate Bar Target Cross-Section With TRP Camera.

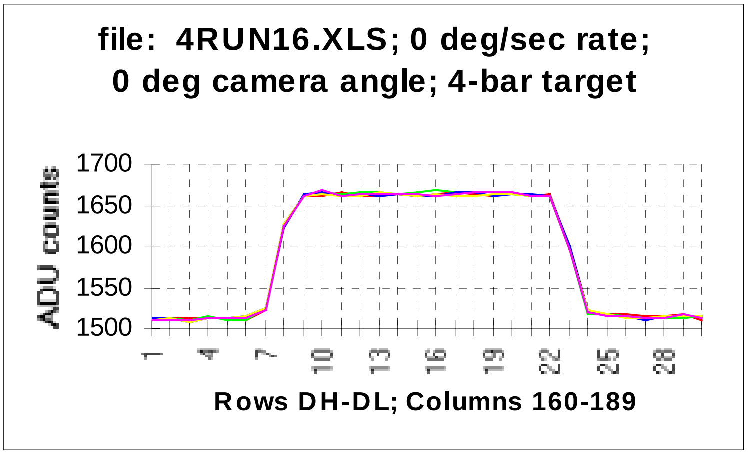

Figure 10. Stationary Bar Target Cross-Section With Sentinel Camera.

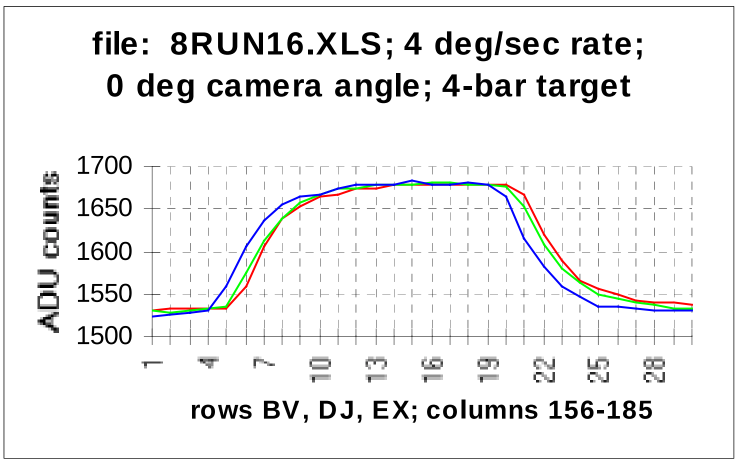

Figure 11. 4 Degrees/Second Rotation Rate Bar Target Cross-Section With Sentinel Camera.